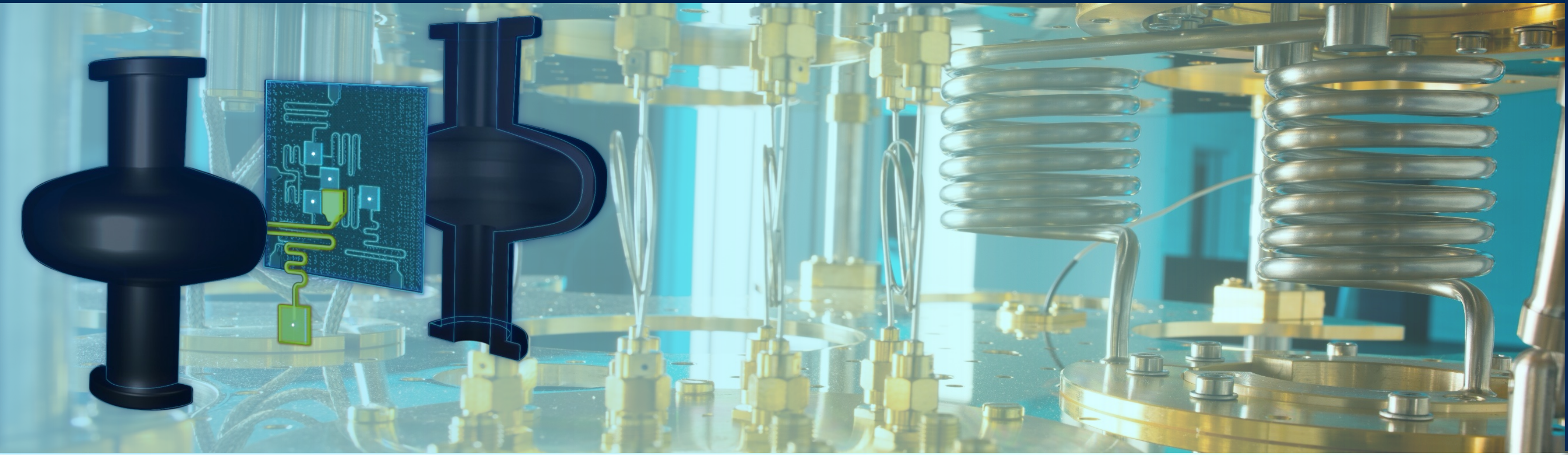
FERMILAB-SLIDES-24-0034-SQMS



This material is based upon work supported by the U.S. Department of Energy, Office of Science, National Quantum Information Science Research Centers, Superconducting Quantum Materials and Systems Center (SQMS) under contract number DE-AC02-07CH11359

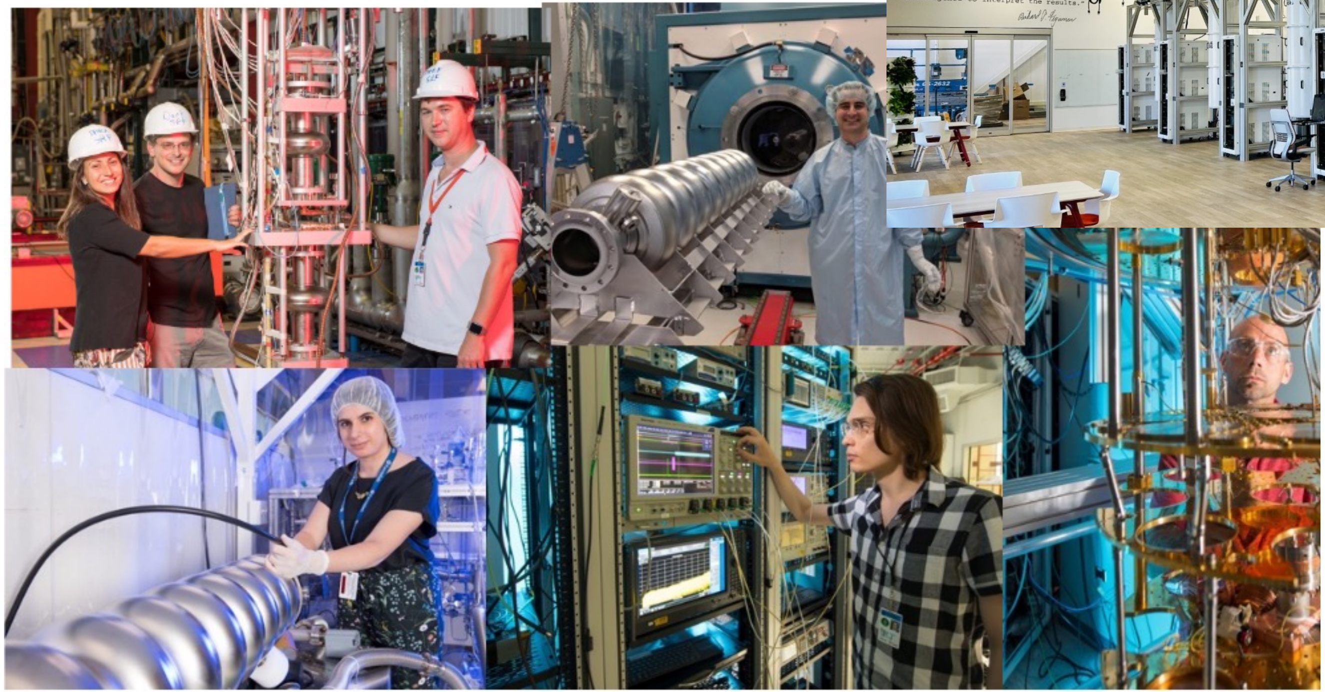
Wavelike Dark Matter Searches with SRF Cavities and Superconducting Qubits at SQMS

Raphael Cervantes
SQMS, Fermilab

Outline

1. Motivation for ultra-high Q haloscopes
2. **SERAPH**: SRF haloscopes for wavelike dark matter searches
    1. Dark photon dark matter searches.
    2. Widely-tunable SRF cavities.
    3. Mitigating SQL noise with transmon qubits.
    4. Axion searches with magnetically-resilient SRF cavities

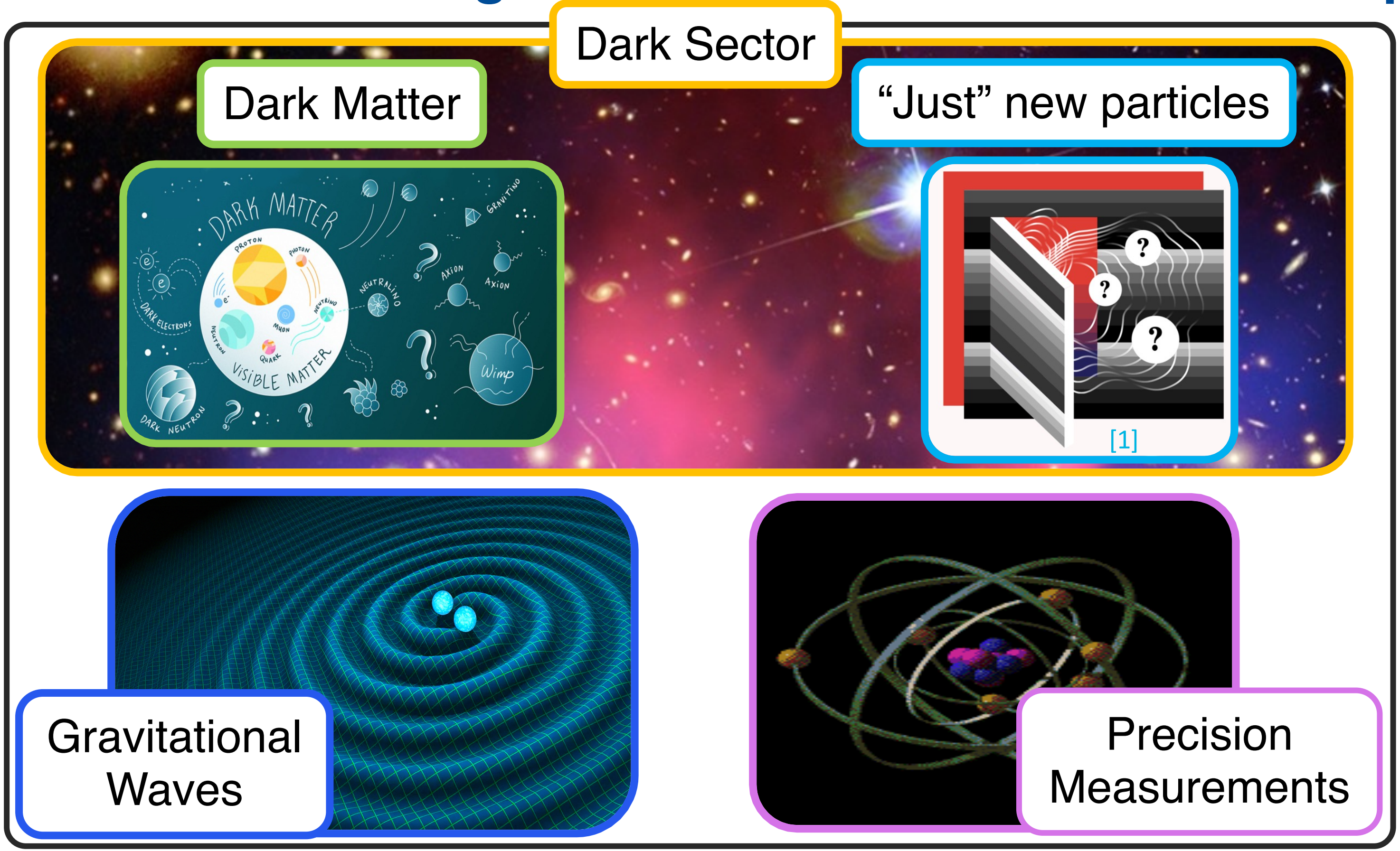
SQMS and Fermilab



How far can we push quantum sensors and superconducting technology for fundamental physics searches?

Credit: A. Grasselino

Quantum Sensing: new windows into fundamental physics



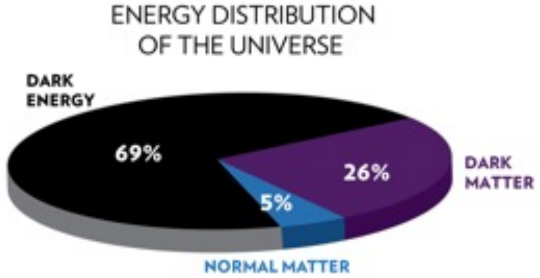
Fermilab Dark SRF Experiment

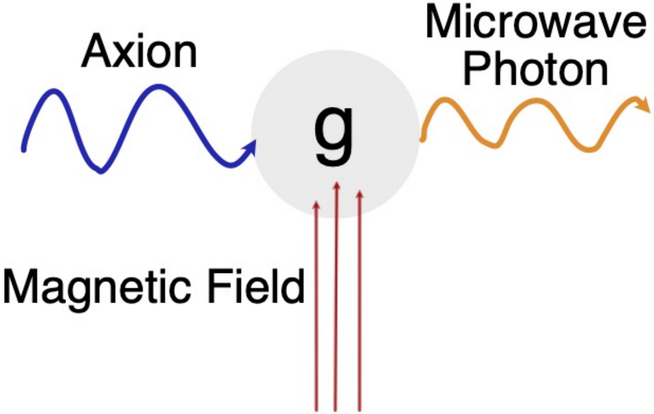
[1] Artwork by Sandbox Studio Chicago with A. Kova
symmetrymagazine.org

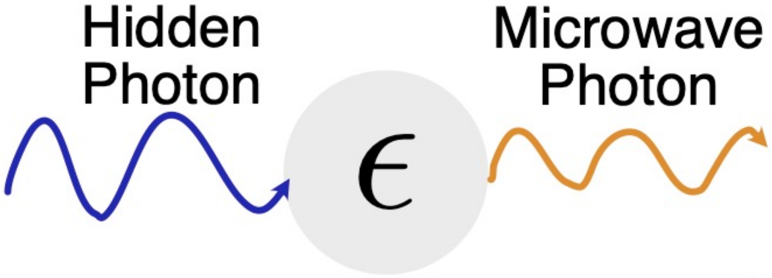
For this talk, we focus on dark matter

What is Dark Matter?

Can it be Axions? Dark Photons?





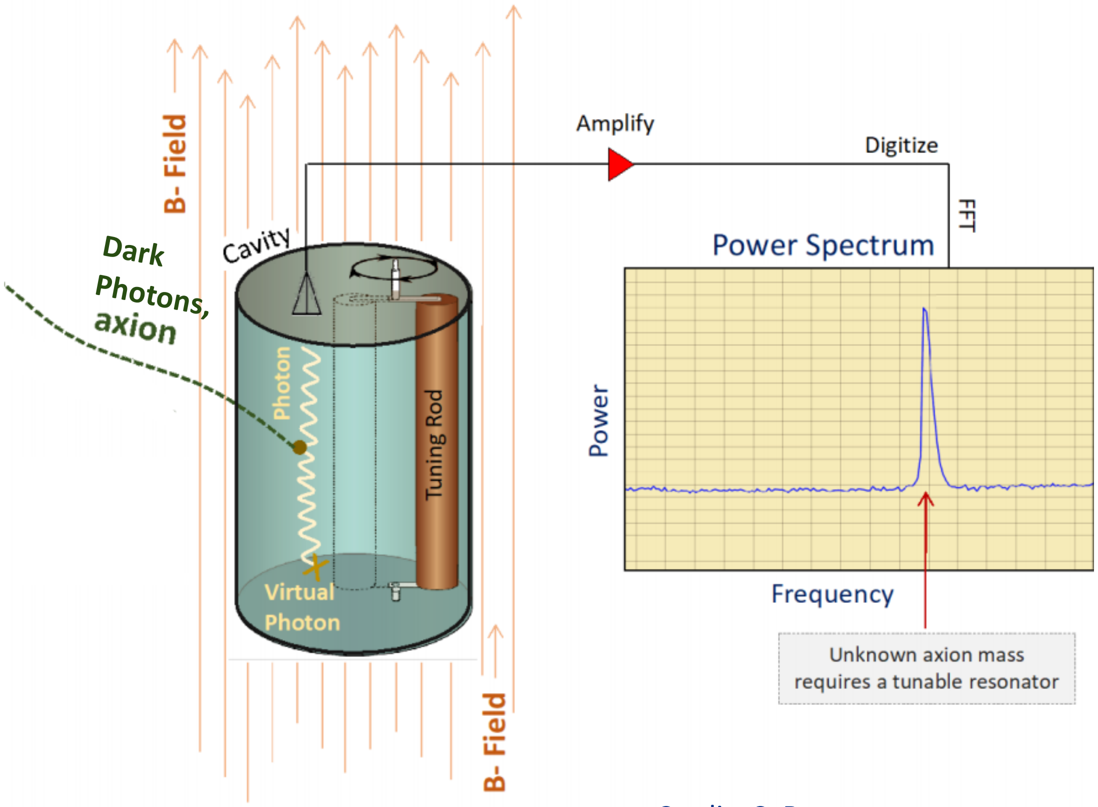


Credit: A. Dixit

Feeble interaction with photons.

We can look for that.

Haloscope Search for Dark Matter



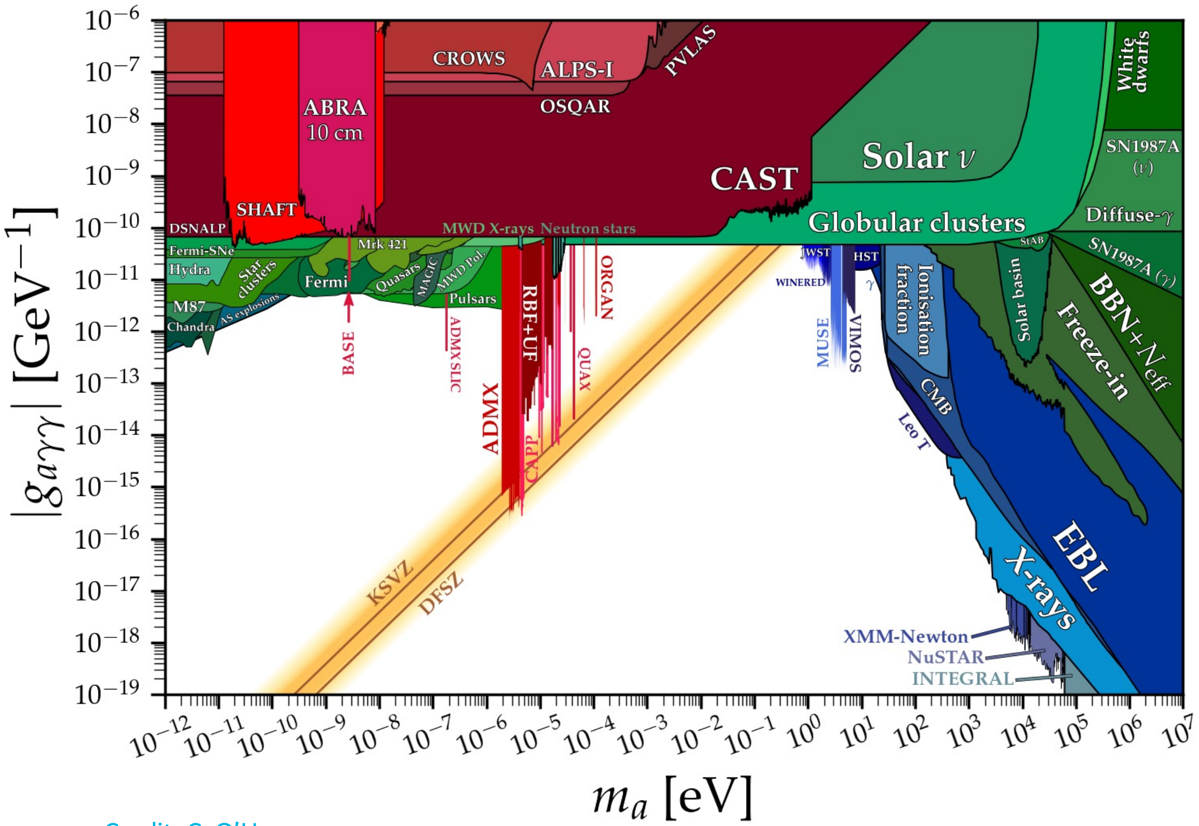
Credit: C. Boutan

Microwave cavities can be used to detect dark photons and axions.

Dark photon searches don't need B-field.

Looking for $< 10^{-24}$ W signal over wide range of frequencies.

No axions were found (yet).



Credit: C. O'Hare

- No discovery, but still progress because of the excluded parameter space.
- But a lot more parameter space left to explore.

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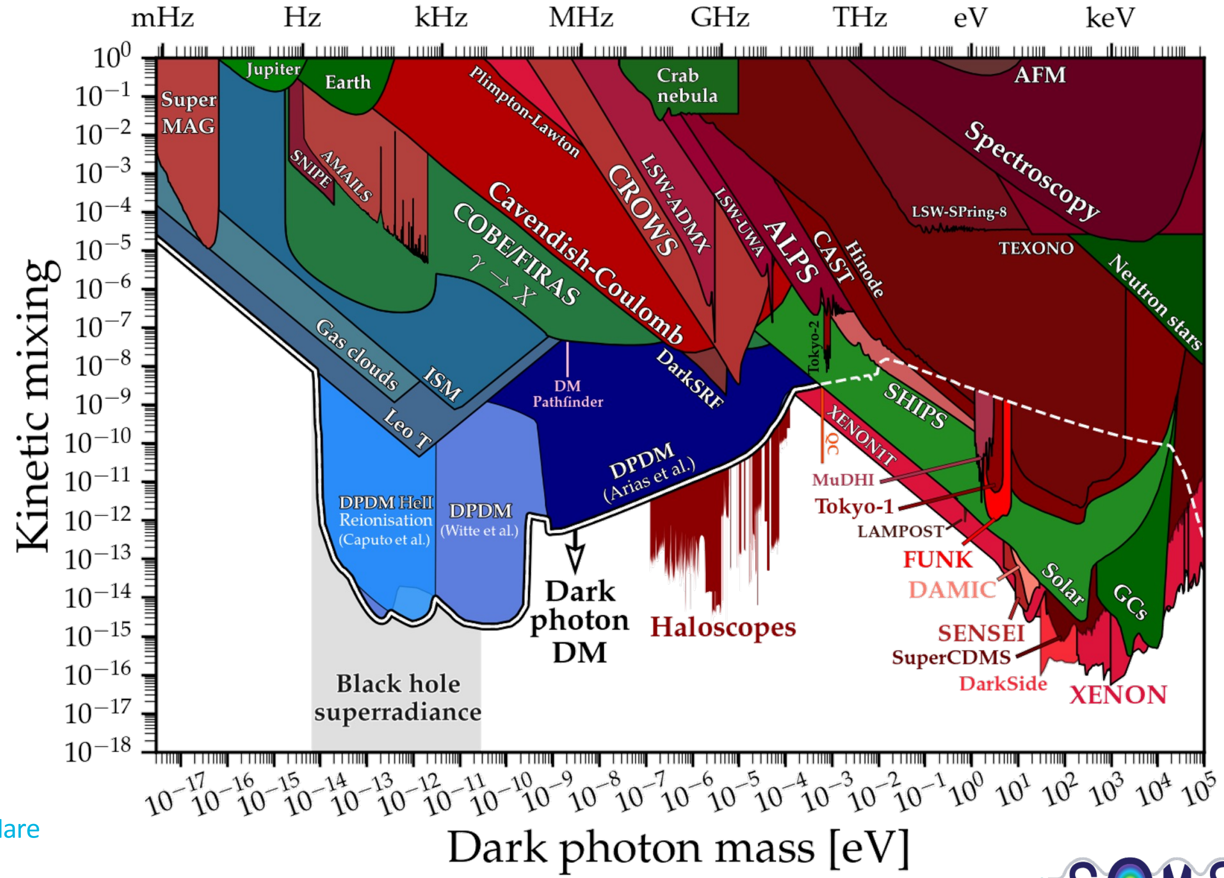
No dark photons have been found yet either.



Credit: C. O'Hare

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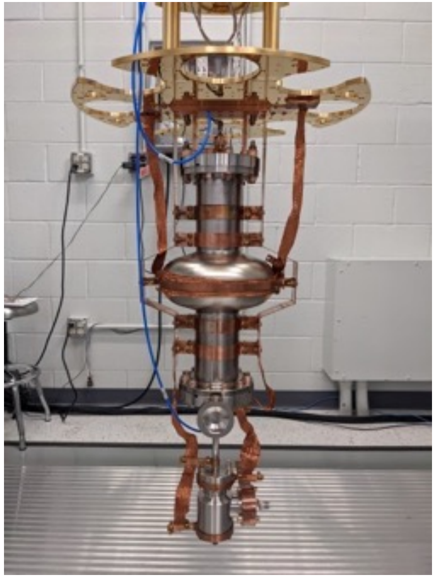
SRF Cavities for Dark Matter Searches



Compared to copper-based searches

Credit: N. Du

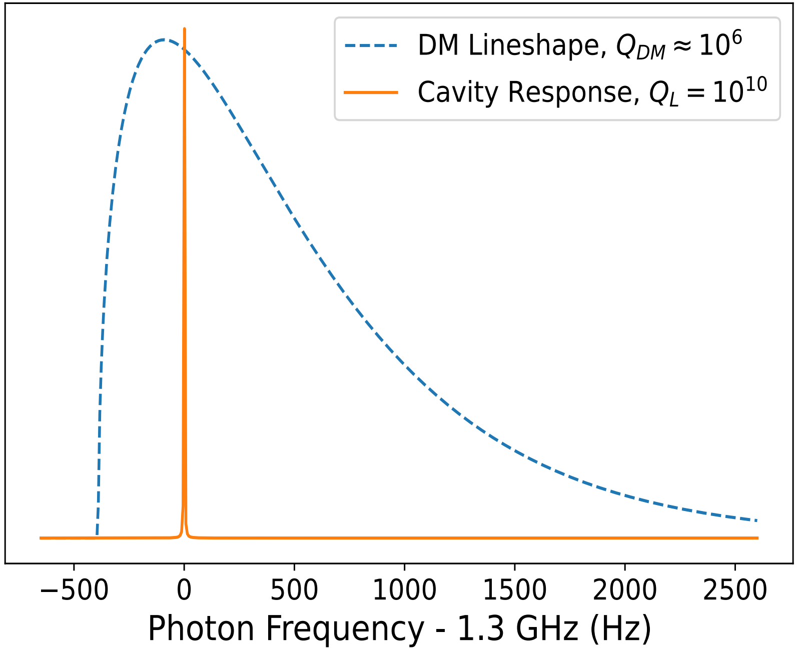
SQMS → $Q \approx 10^{10}$

ADMX and CAPP → $Q \approx 10^{5}$

High Q allows for larger signal and lower noise floor.

Possibly factor 10^5 increase in instantaneous scan rate.

Instantaneous scan rate is proportional to Q_L



For virialized axions

$$\frac{\mathrm{d}f}{\mathrm{d}t} \sim Q_L Q_{DM} \left(\frac{\eta \chi^2 m_{A'} \rho_{A'} V_{eff} \beta}{\mathrm{SNR} T_n (\beta + 1)} \right)^2$$

even if $Q_L \gg Q_{DM}$

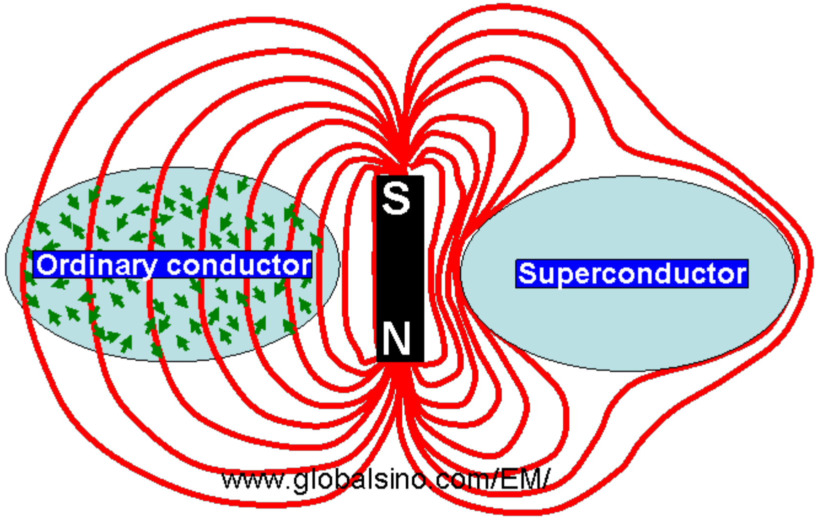
- Signal power $P_s \propto \min(Q_L, Q_{DM})$
- Noise power reduces with Q_L.
- Tuning steps $\Delta f \propto \Delta f_{DM}$. Cavity sensitive to distribution of possible DM rest masses.

More details: arXiv:2208.03183

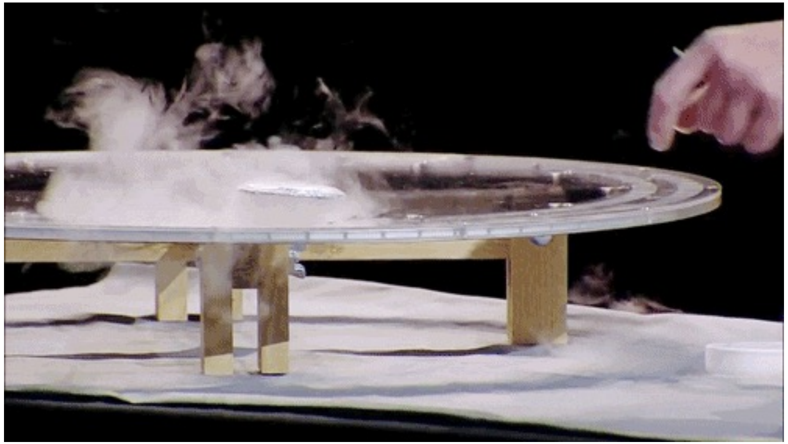
There's a catch though…

Superconductors don't like magnetic fields (Meissner effect).

Magnetic fields can destroy superconductivity.



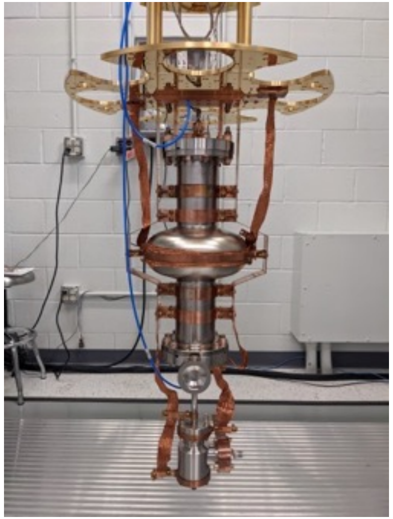
Credit: TED



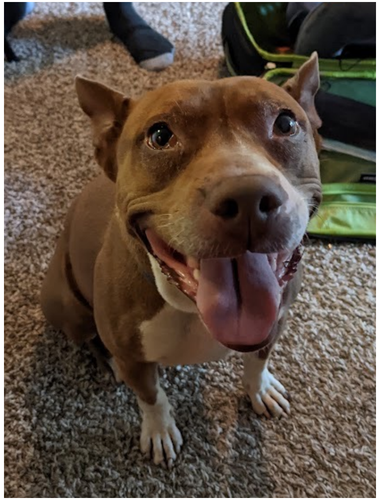
We need the magnetic field to look for axions. More on this later, but we can still use superconducting cavities without a magnetic field to look for dark photons.

SERAPH: SupERconducting Axion and Paraphoton Haloscope

Family of SQMS SRF haloscope experiment. Name works on different levels.



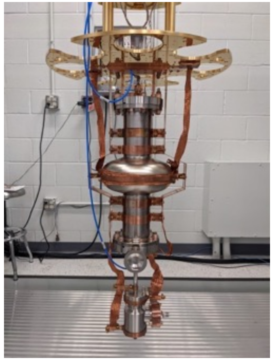
SRF



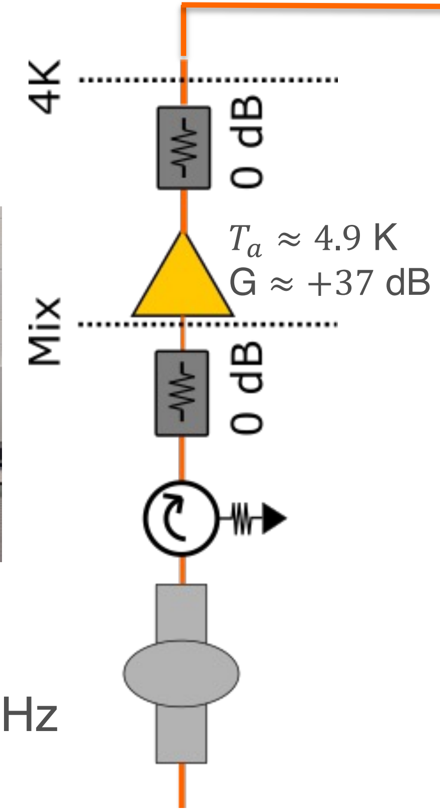
Seraphine

Sir Raph(ael)

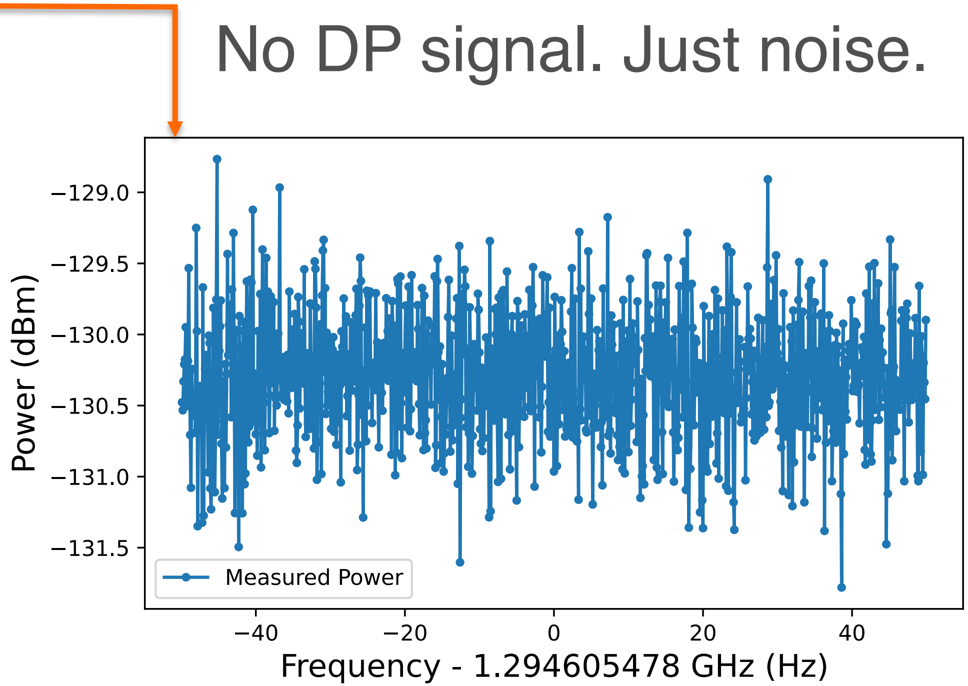
SERAPHv1: Parasitic Search for Dark Photons



$T_c \approx 35$ mK
$Q_L \approx 5\times10^9$
$f_0 = 1.295$ GHz
$\beta \sim 1.3$

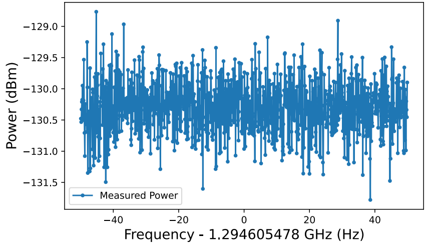


No DP signal. Just noise.

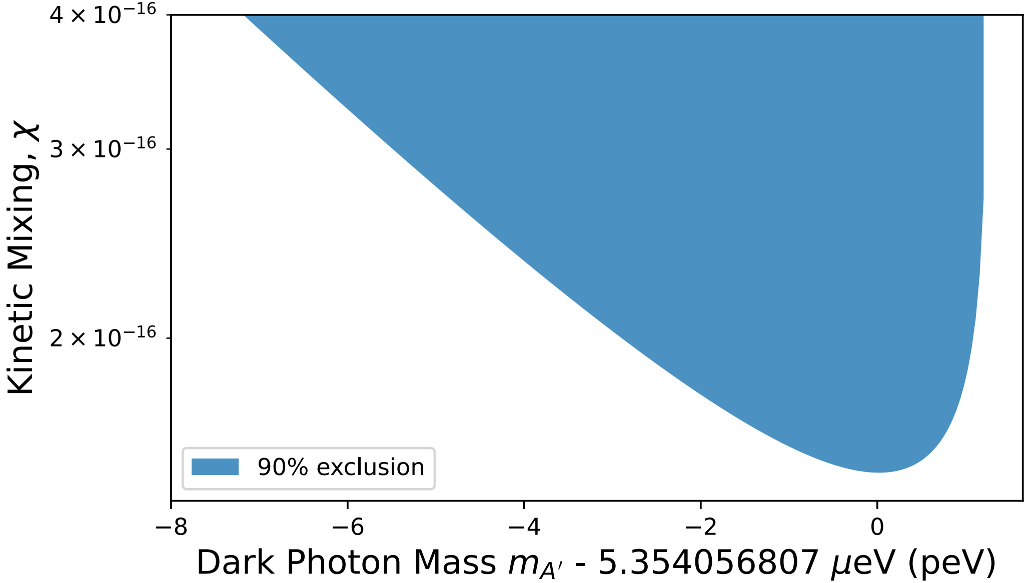


1000 seconds integration time

Excluded Dark Photon Parameter Space



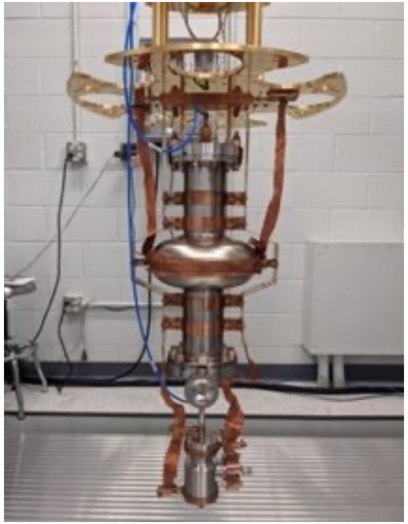
haloscope analysis

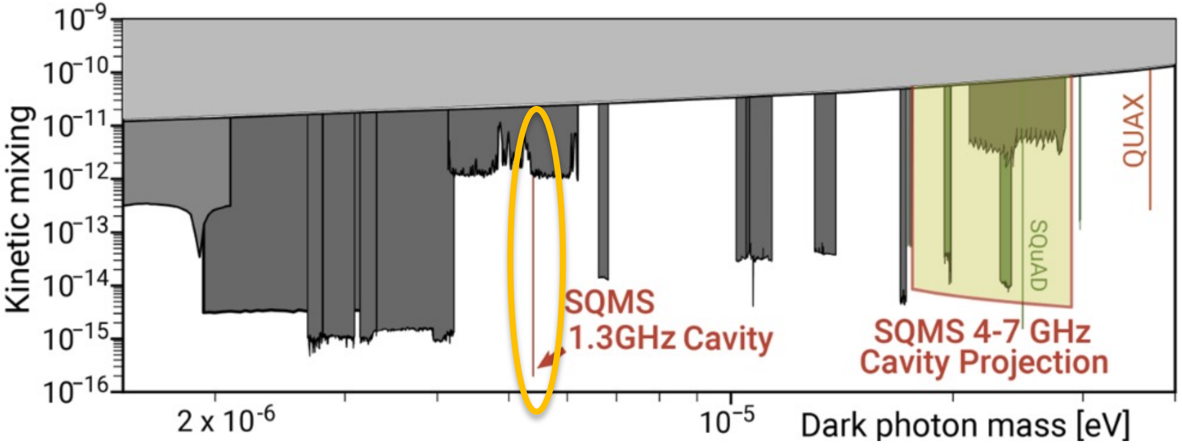


arXiv:2208.03183

In review purgatory. Measurements recently performed to address reviewer comments.

Deepest sensitivity: Ultrahigh Q for Dark photon DM





Cervantes et al., arXiv:2208.03183v3 (2022)

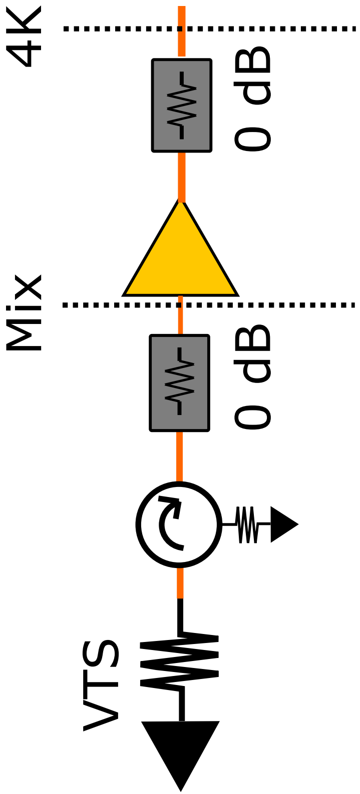
DPDM search in DR with 1.3 GHz cavity with $Q_0 \approx 10^{10}$.

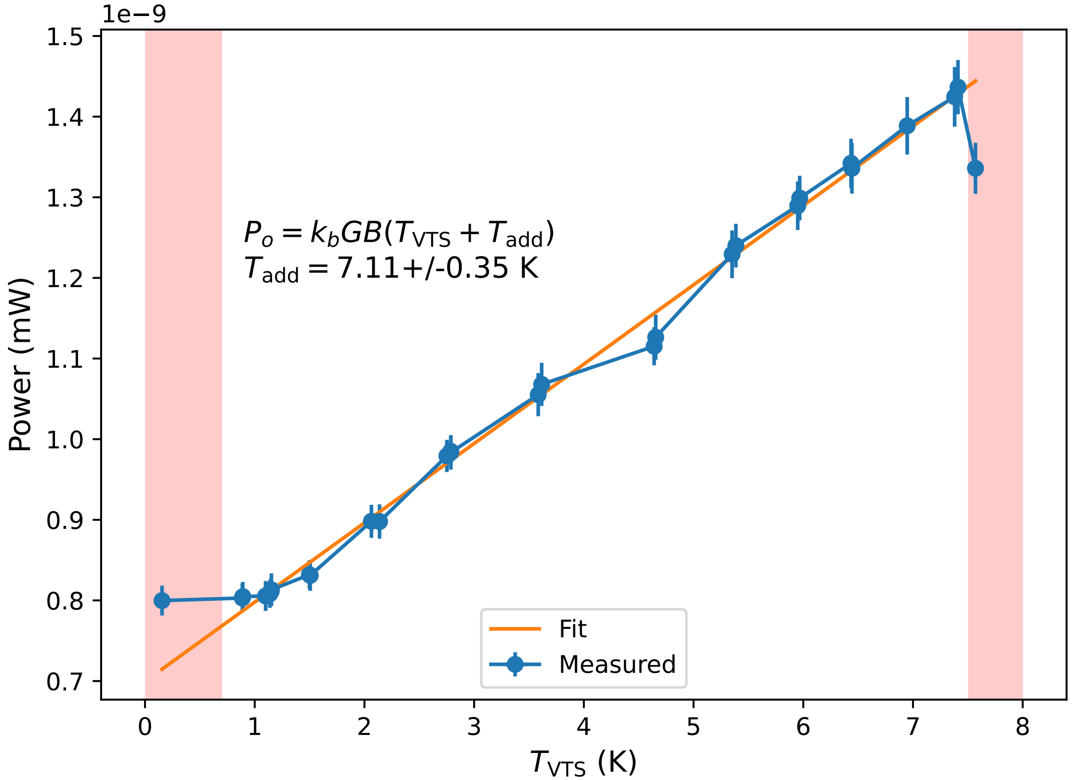
Deepest exclusion to wavelike DPDM by an order of magnitude.

Next steps:

- Tunable DPDM search from 4-7 GHz ("low hanging fruit")
- Implement photon counting to subvert SQL noise limit.

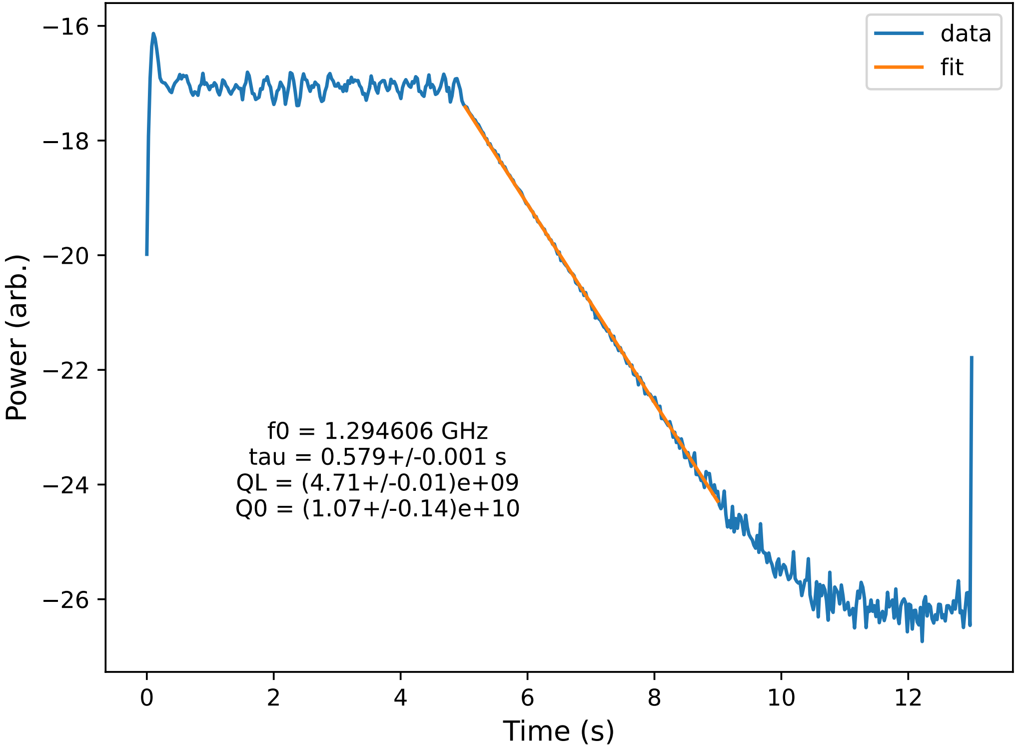
Noise calibration with Variable Temperature Stage



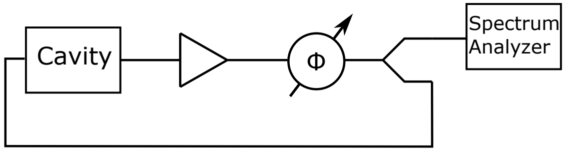


T_{add} consistent with 4.6 K amplifier noise and 2 dB insertion loss.

Measure Q with decay measurement

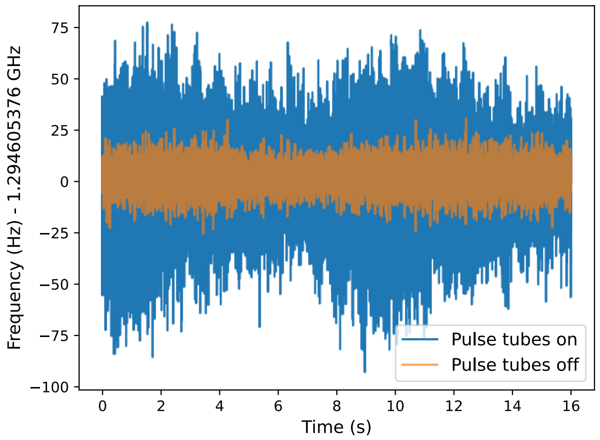


Microphonics

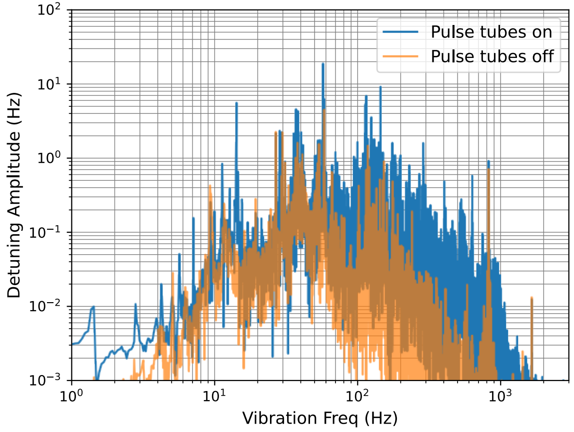


- Measured with self-excitation loop and phase noise analyzer+spectrum analyzer.
- 25 Hz RMS
- Mitigated by turning off pulse tubes (7 Hz RMS), but not viable for a dark matter search.

PNA measurement



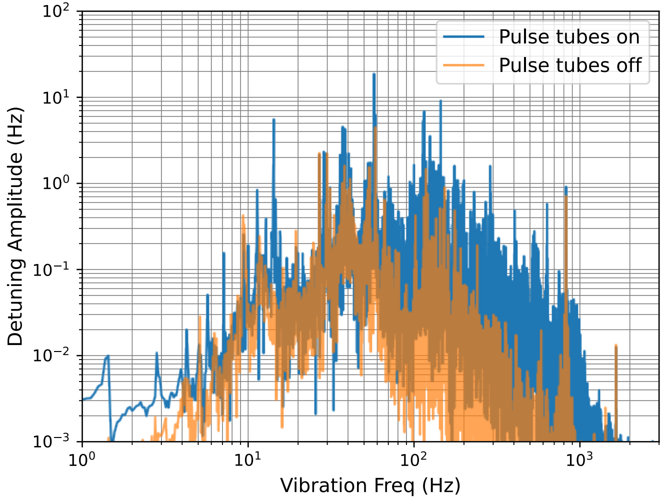
FFT of PNA measurement



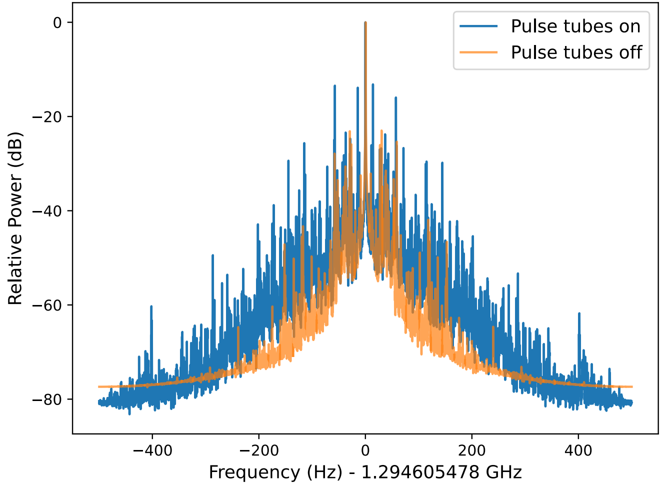
Microphonics and Frequency Modulation

Creates modulation of dark matter signal. Power gets spread into sidebands.

FFT of PNA measurement



SA measurement



Modulation Frequency f_m (Hz)	Detuning Amplitude f_Δ (Hz)	Modulation Index $\frac{f_m}{f_\Delta}$	Carrier amplitude (dBc)	Sideband amplitude (dBc)
14.3	5.5	0.4	-0.32	-14.5
57.2	18.2	0.3	-0.22	-16.1

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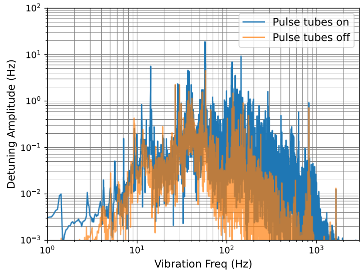
Microphonics and Frequency Modulation

Creates modulation of dark matter signal. Power gets spread into sidebands.



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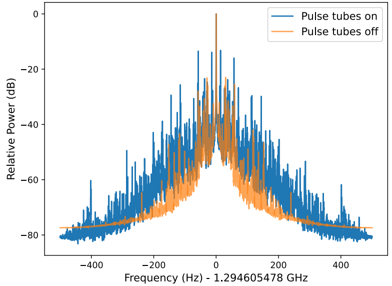
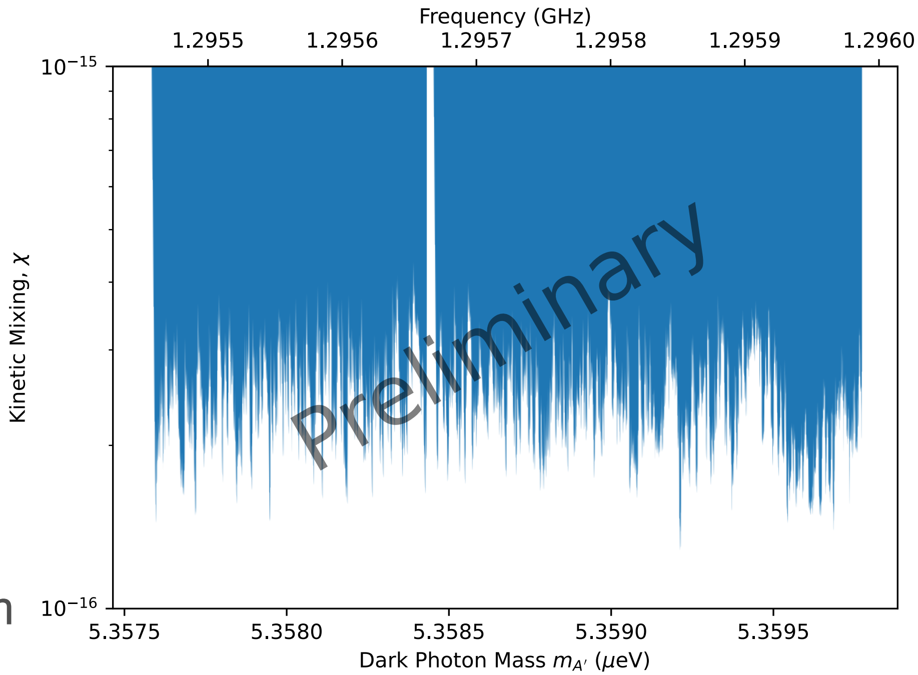


Carrier band attenuated by 0.54 dBc.

DM signal attenuated $\boldsymbol{\eta \approx 0.88}$

Might recover if analysis looks for sidebands.

Tunable search with 1.3 GHz Cavity (SERAPH v1.1)



Similar 1.3 GHz cavity in liquid helium bath. Tunes by mechanical compression for 500 kHz tuning range. T_{cav} = 1.4 K, Q_L = 2.4e8. Very overcoupled.

Similar experiment posted by Chinese collaboration

SRF Cavity Searches for Dark Photon Dark Matter: First Scan Results

Zhenxing Tang,[1,2,*] Bo Wang,[3,*] Yifan Chen,[4] Yanjie Zeng,[5,6] Chunlong Li,[5] Yuting Yang,[5,6] Liwen Feng,[1,7] Peng Sha,[8,9,10] Zhenghui Mi,[8,9,10] Weimin Pan,[8,9,10] Tianzong Zhang,[1] Yirong Jin,[11] Jiankui Hao,[1,7] Lin Lin,[1,7] Fang Wang,[1,7] Huamu Xie,[1,7] Senlin Huang,[1,7] and Jing Shu[1,2,12,†]

[1]*School of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China*
[2]*Beijing Laser Acceleration Innovation Center, Huairou, Beijing, 101400, China*
[3]*International Centre for Theoretical Physics Asia-Pacific, University of Chinese Academy of Sciences, 100190 Beijing, China*
[4]*Niels Bohr International Academy, Niels Bohr Institute, Blegdamsvej 17, 2100 Copenhagen, Denmark*
[5]*CAS Key Laboratory of Theoretical Physics, Institute of Theoretical Physics, Chinese Academy of Sciences, Beijing 100190, China*
[6]*School of Physical Sciences, University of Chinese Academy of Sciences, No. 19A Yuquan Road, Beijing 100049, China*
[7]*Institute of Heavy Ion Physics, Peking University, Beijing 100871, China*
[8]*Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China*
[9]*Key Laboratory of Particle Acceleration Physics and Technology, Chinese Academy of Sciences, Beijing 100049, China*
[10]*Center for Superconducting RF and Cryogenics, Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China*
[11]*Beijing Academy of Quantum Information Sciences, Beijing 100193, China*
[12]*Center for High Energy Physics, Peking University, Beijing 100871, China*

(Dated: May 26, 2023)

We present the first use of a tunable superconducting radio frequency cavity to perform a scan search for dark photon dark matter with novel data analysis strategies. We mechanically tuned the resonant frequency of a cavity embedded in the liquid helium with a temperature of 2 K, scanning the dark photon mass over a frequency range of 1.37 MHz centered at 1.3 GHz. By exploiting the superconducting radio frequency cavity's considerably high quality factors of approximately 10^{10}, our results demonstrate the most stringent constraints to date on a substantial portion of the exclusion parameter space, particularly concerning the kinetic mixing coefficient between dark photons and electromagnetic photons ϵ, yielding a value of $\epsilon < 2.2 \times 10^{-16}$.

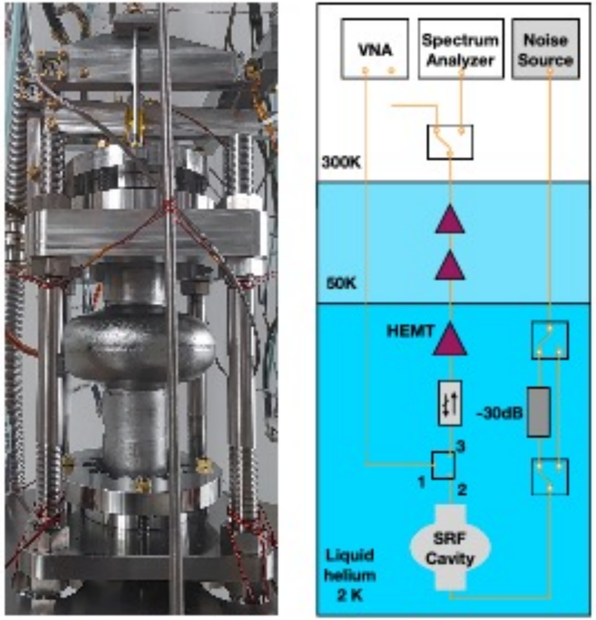
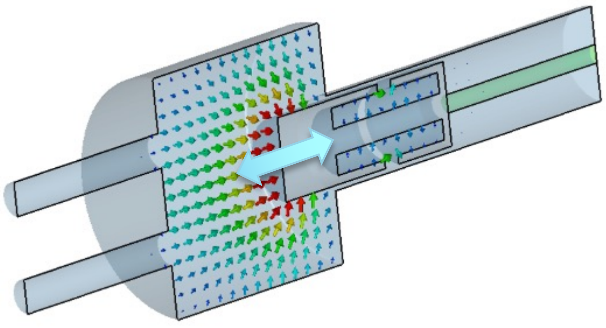


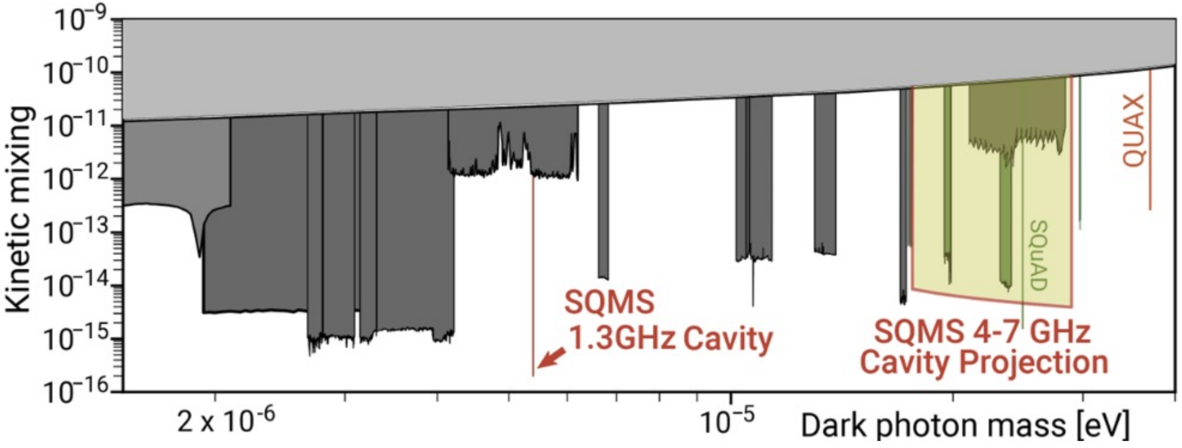
FIG. 1: Left: the single-cell SRF cavity equipped with frequency tuner. Right: Schematic of the microwave electronics for DPDM searches. The VNA measures the net amplification factor $G_{\rm net}$ of the amplifier circuit consisting of an isolator, a HEMT amplifier and two room-temperature amplifiers. The noise source and the spectrum analyzer calibrate the resonant frequencies f_0^i. The time-domain signals from the SRF, with sequential amplification, are finally recorded by the spectrum analyzer.

LHe vertical test stand facility at Fermilab

Deepest sensitivity: Ultrahigh Q for Dark photon DM



“plunger” cavity
4-7 GHz



Cervantes et al., arXiv:2208.03183v3 (2022)

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Next steps:

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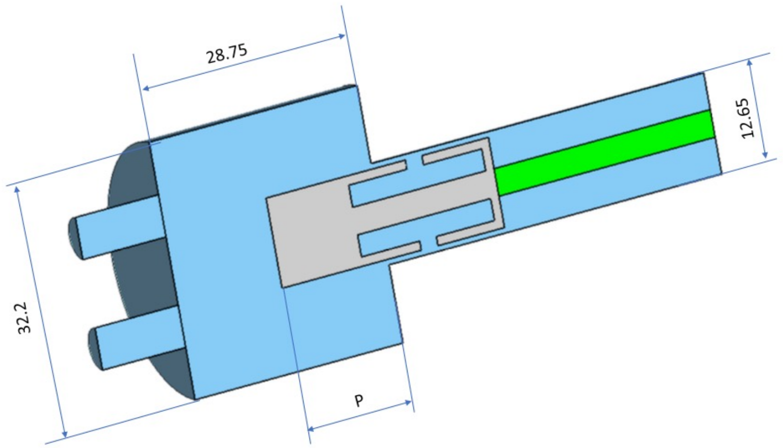
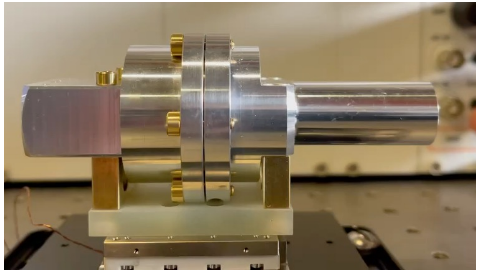
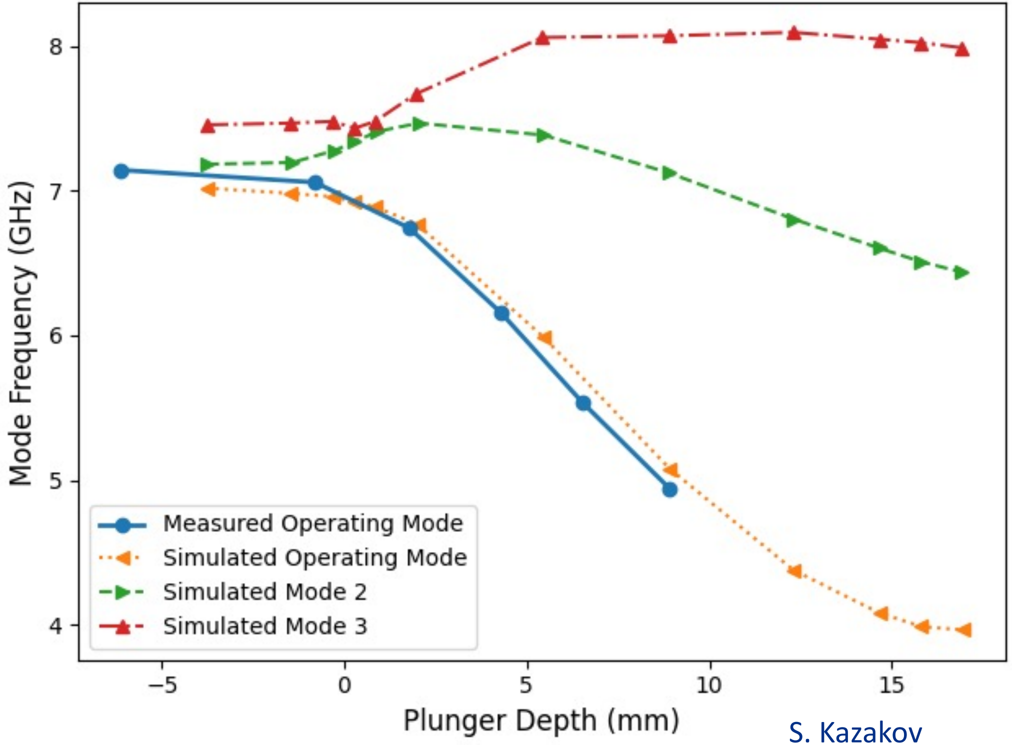
- Implement photon counting to subvert SQL noise limit.

Simulated and measured modes



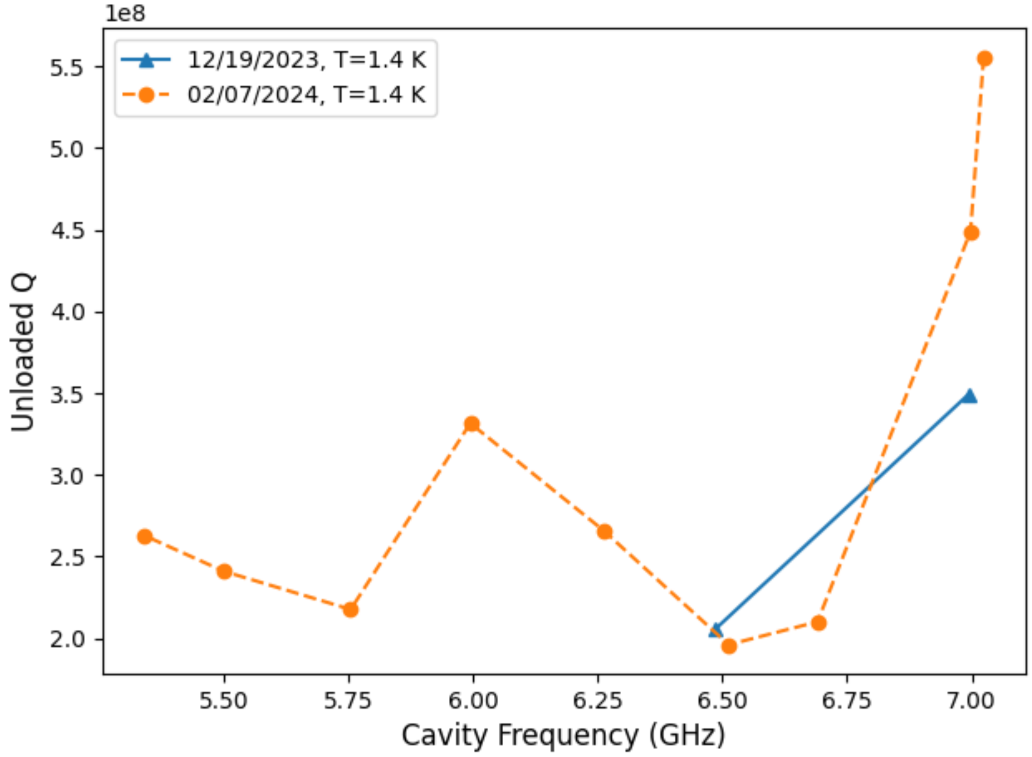




S. Kazakov

Straightforward tuning. No mode crossings. Good agreement between measurement and simulation.

Measured Unloaded Q with decay measurement

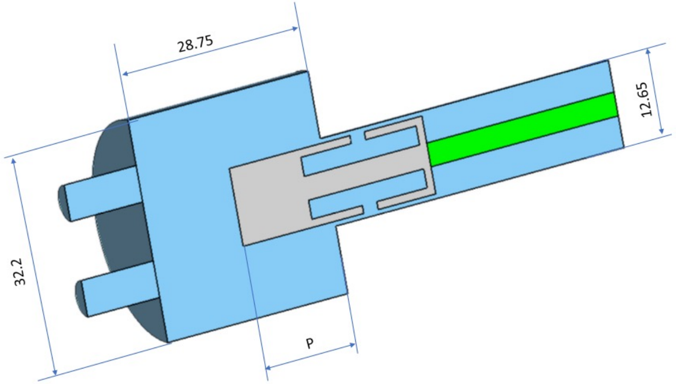


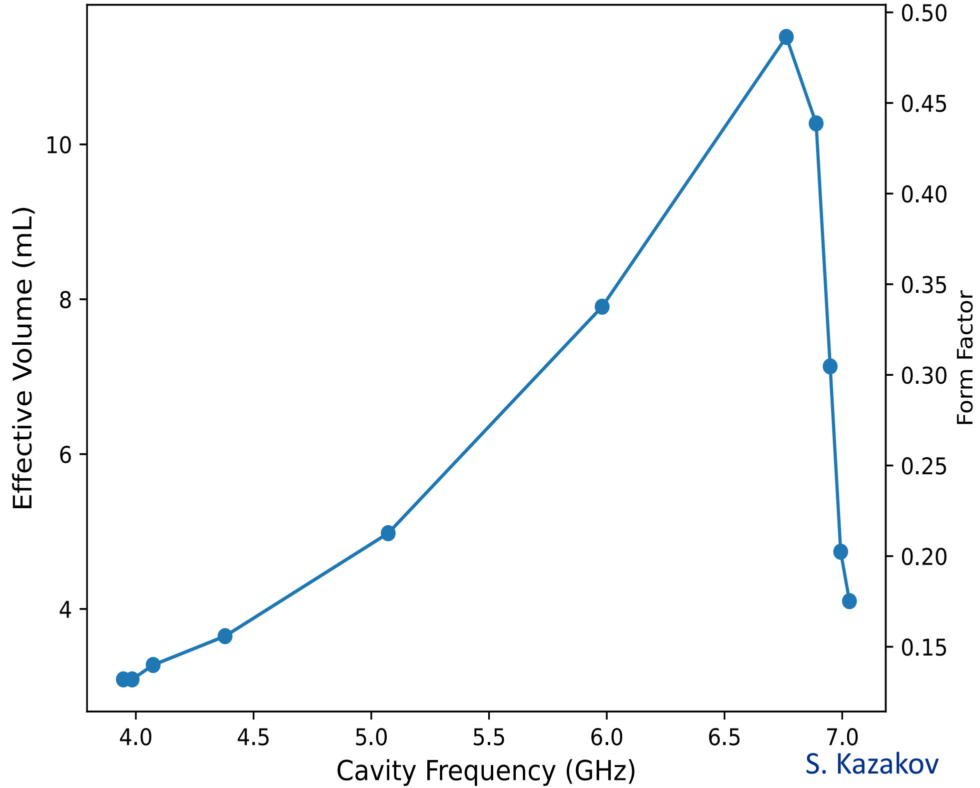
Cavity Q is acceptable for now.

Surface resistance could be reduced with more optimized surface treatment.

Simulated effective volume

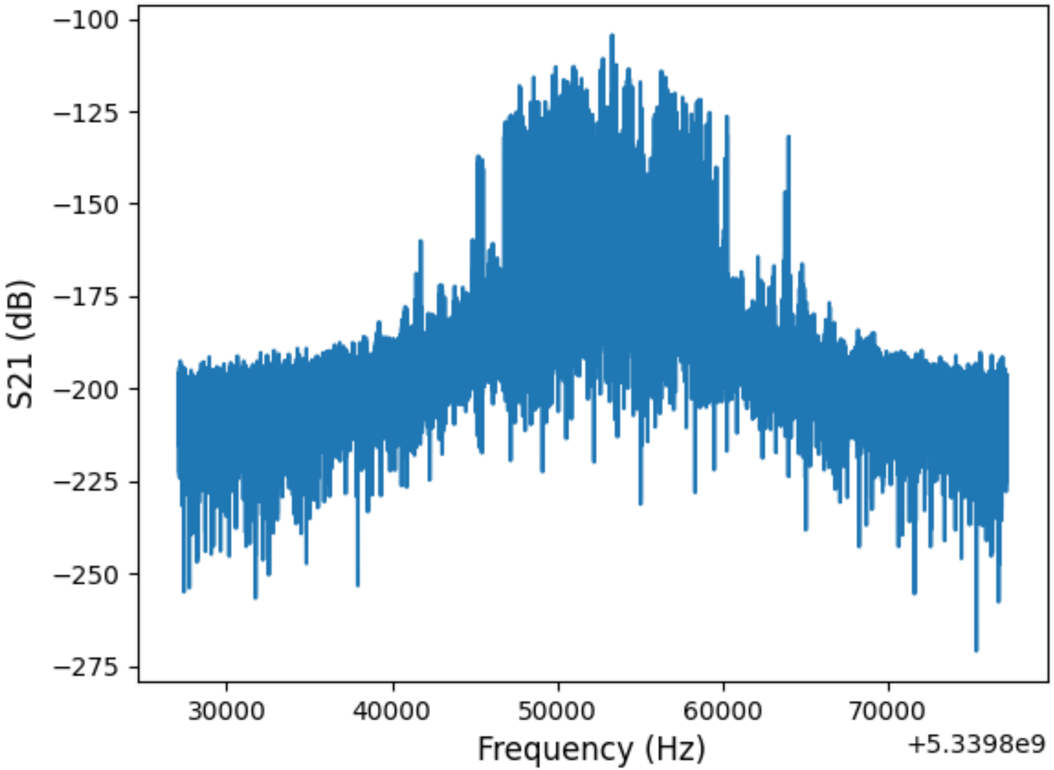
$$V_{\text{eff}} = \frac{\left|\int dV\, E_z\right|^2}{\int dV\, |\mathbf{E}|^2}$$





Lots of microphonics in a helium bath

Resonance looks like this with a VNA.



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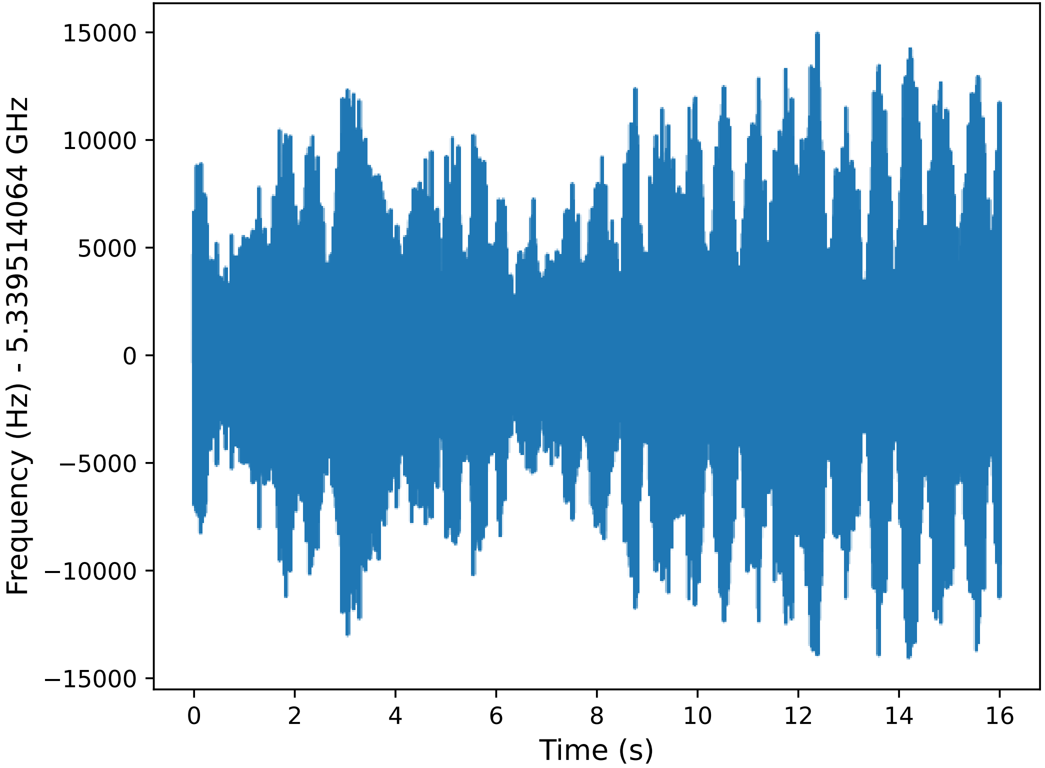
Microphonics with SEL + Phase Noise Analyzer

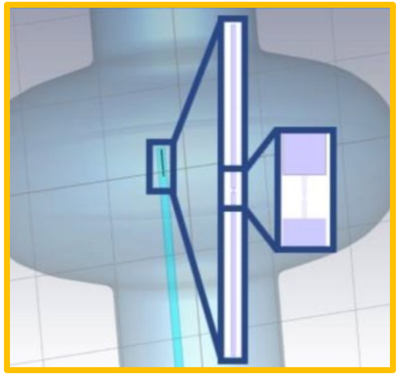


Can destabilize microphonics if there's too much energy in the system.

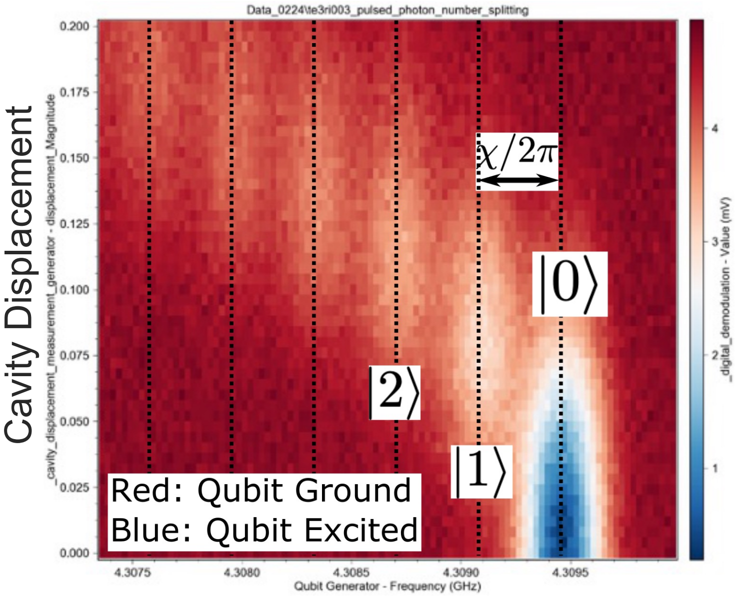
The RMS of the microphonics is 4.6 kHz!

Currently brainstorming how to mitigate.

Subverting SQL noise with qubit-based photon counting



Superconducting qubit in SRF cavity.



Quantum protocols counts photons non-destructively.

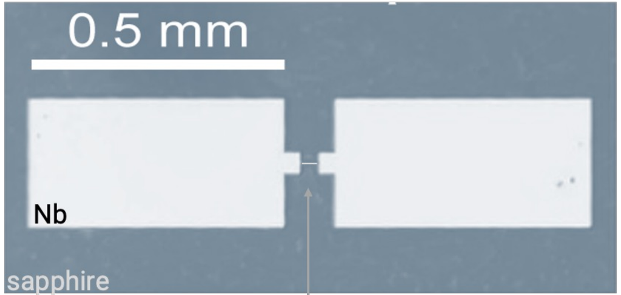
SQL noise: hf/k
240 mK @ 5 GHz

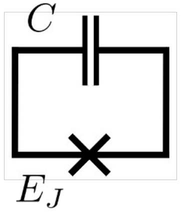
dominates compared to 30 mK thermal photons.

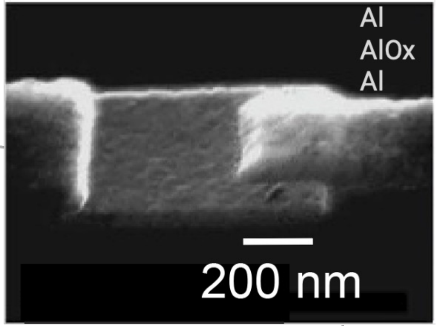
Regularly perform photon counting with dispersive measurements.

Detour: The Transmon Qubit

Transmon device image



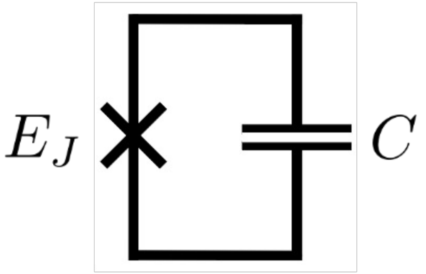




Wang et al., Nature Comm. 5, 5836 (2014)

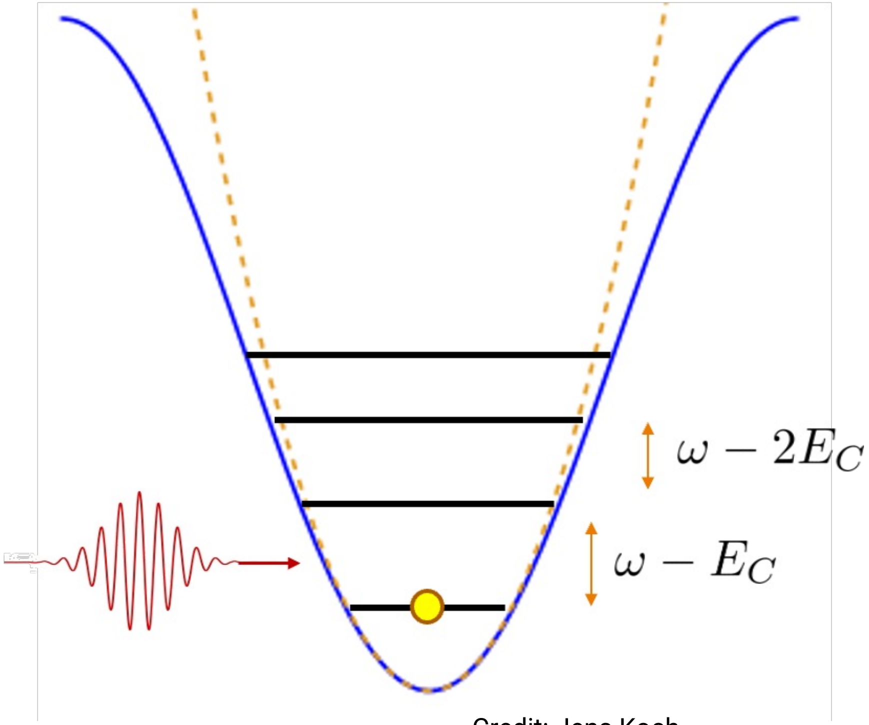
Credit: Jens Koch

Detour: The Transmon Qubit



Introduce nonlinearity: replace inductor with Josephson junction

$$H = \frac{Q^2}{2C} - E_J \cos(\overbrace{2\pi\Phi/\Phi_0}^{\varphi})$$



Credit: Jens Koch

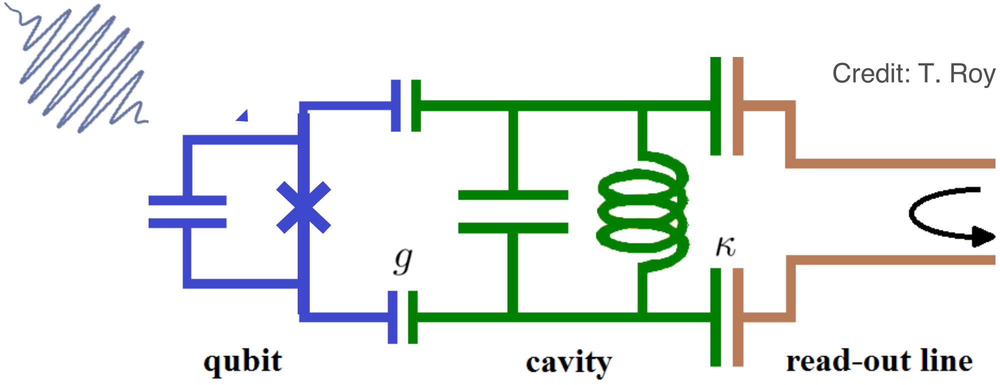
Count Photons with Superconducting Qubits

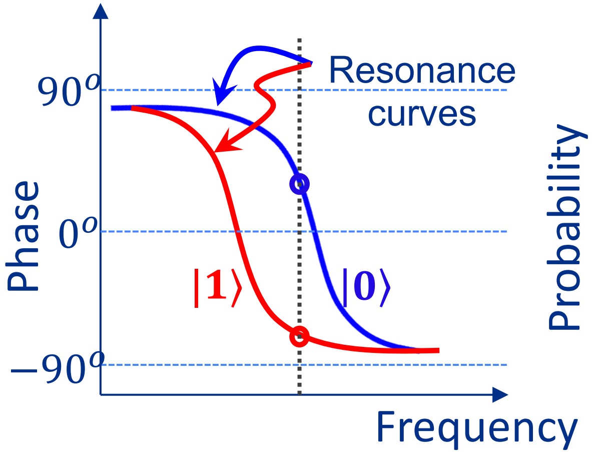
$$\mathcal{H}/\hbar = \omega_c a^\dagger a + \frac{1}{2}(\omega_q + 2\chi a^\dagger a)\sigma_z$$

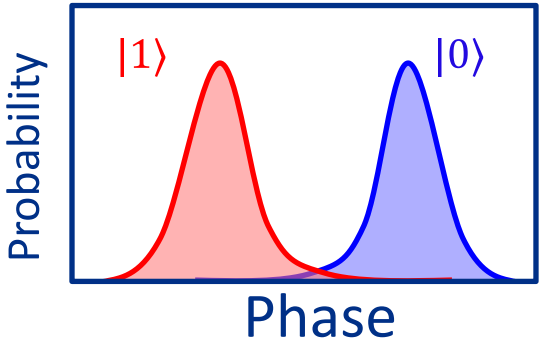
Qubit frequency depends on # of photons.

Can avoid quantum noise if you just count the number of photons and don't try to measure their phase.

We can use superconducting qubits to count microwave photons inside the cavity.

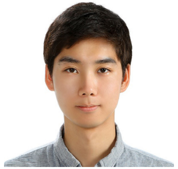




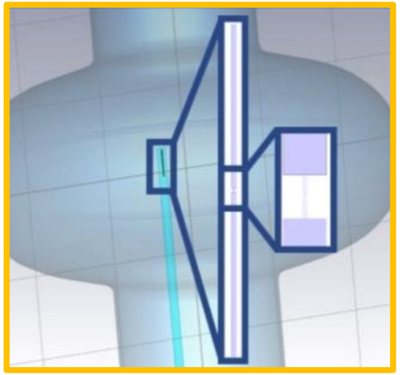


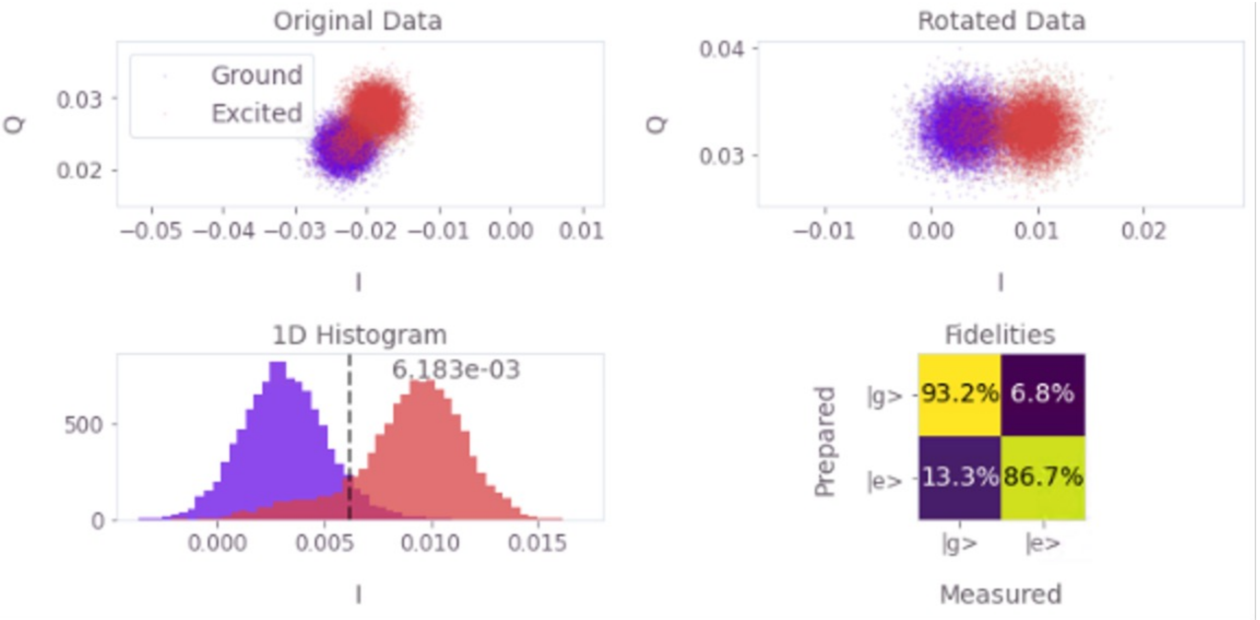
Dilution fridge ~ 10 mK

Current photon counting scheme



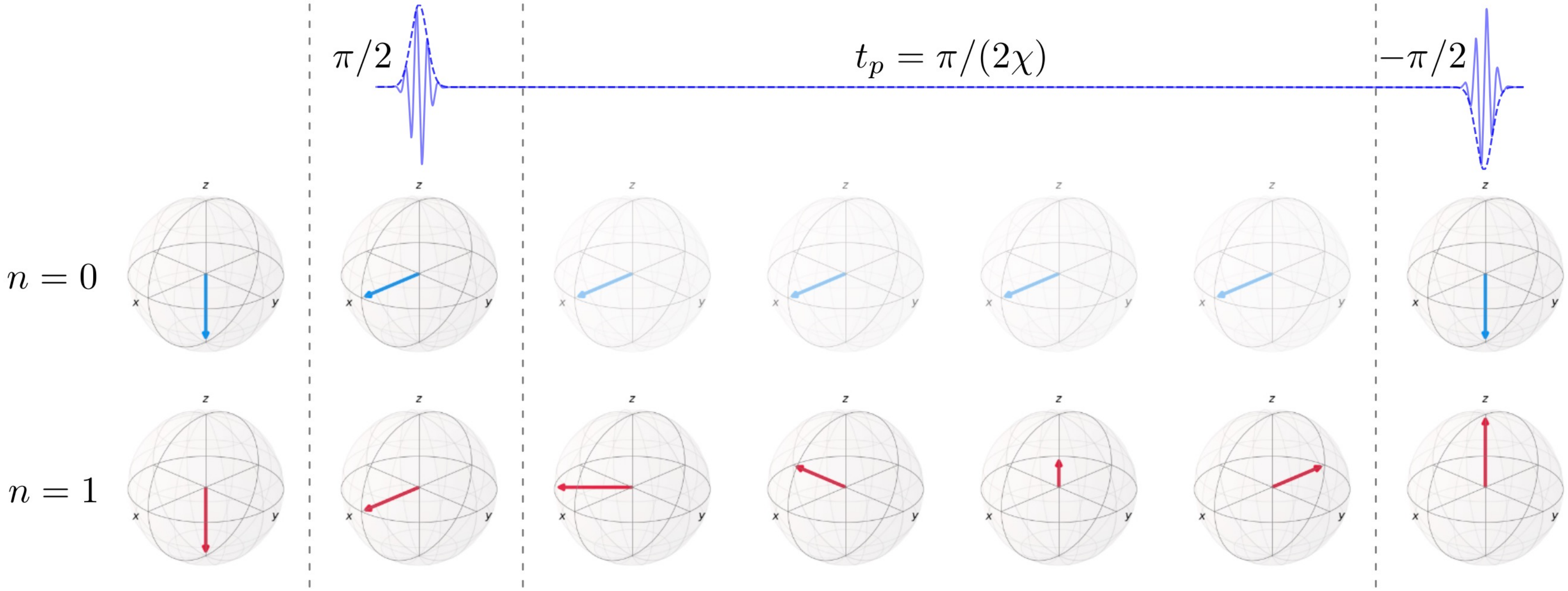
Measurements performed by Taeyoon Kim





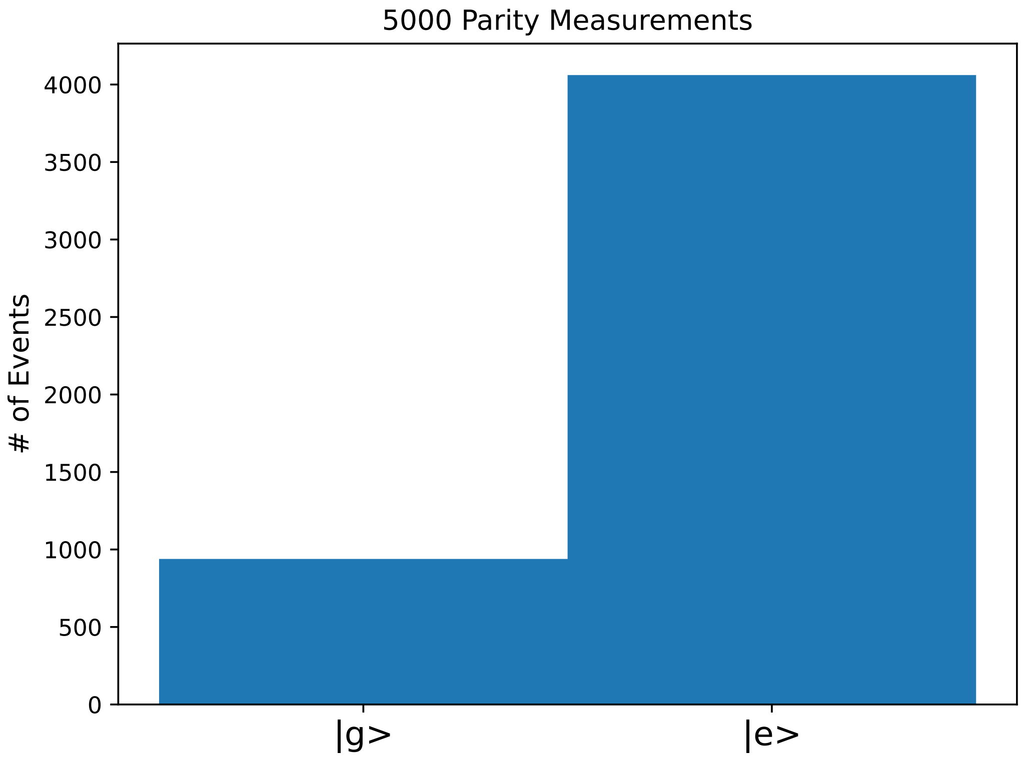
Qubit T1 ~ 150 µs. Readout rate is 1/ms

Parity measurement maps cavity state onto qubit



Credit: A. Dixit

Photon counting results



Parity measurement where qubit is prepared in ground state and we apply two $+\pi/2$ pulses.

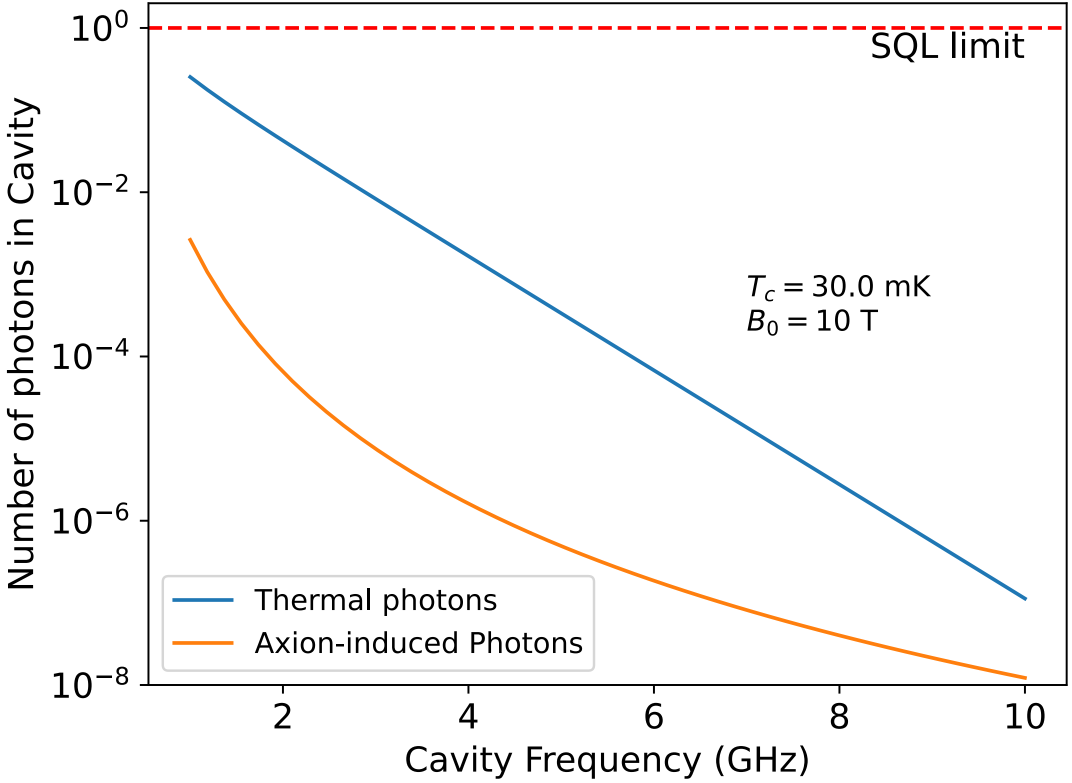
With perfect readout:

|g> corresponds to 1 photon.

|e> corresponds to 0 photon.

Can use fidelity matrix and characteristics of the system to derive dark photon limit.

Why we need photon counting



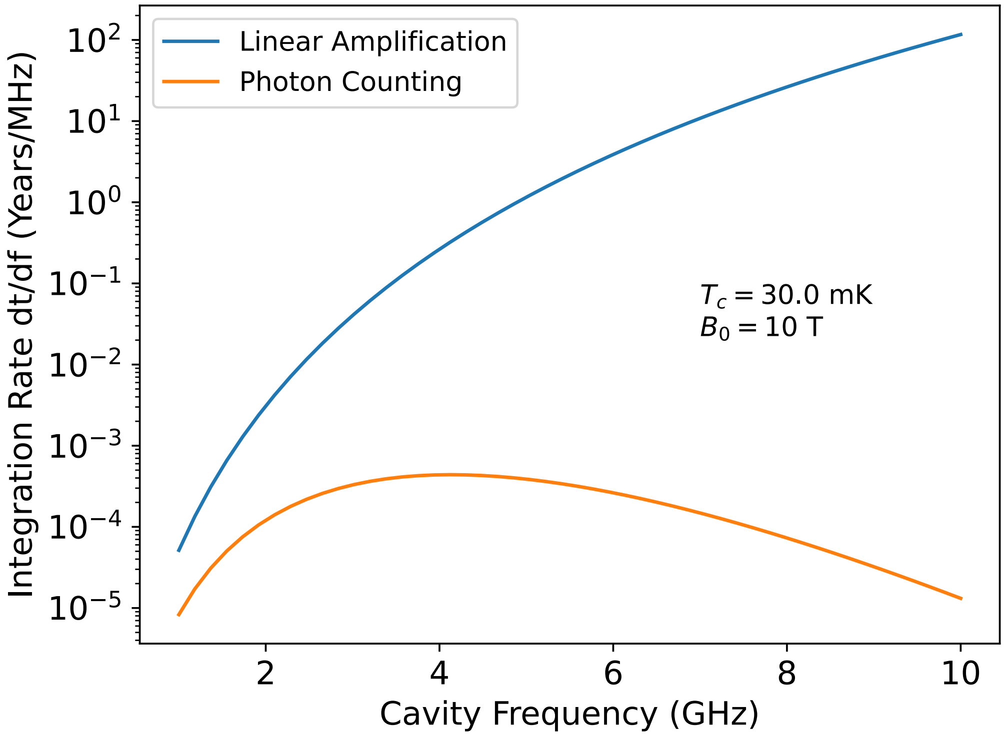
$$V_c = 136\, L \times \left(\frac{f}{1GHz}\right)^{-3}$$

$$Q_L = 80\,000 \times \left(\frac{f}{1GHz}\right)^{-\frac{2}{3}}$$

$$n_c = \frac{1}{\exp\left(\frac{hf}{k_b T}\right) - 1}$$

SQL noise dominates at higher frequencies. Need to mitigate SQL.

Would take long time to scan DFSZ with single cavity



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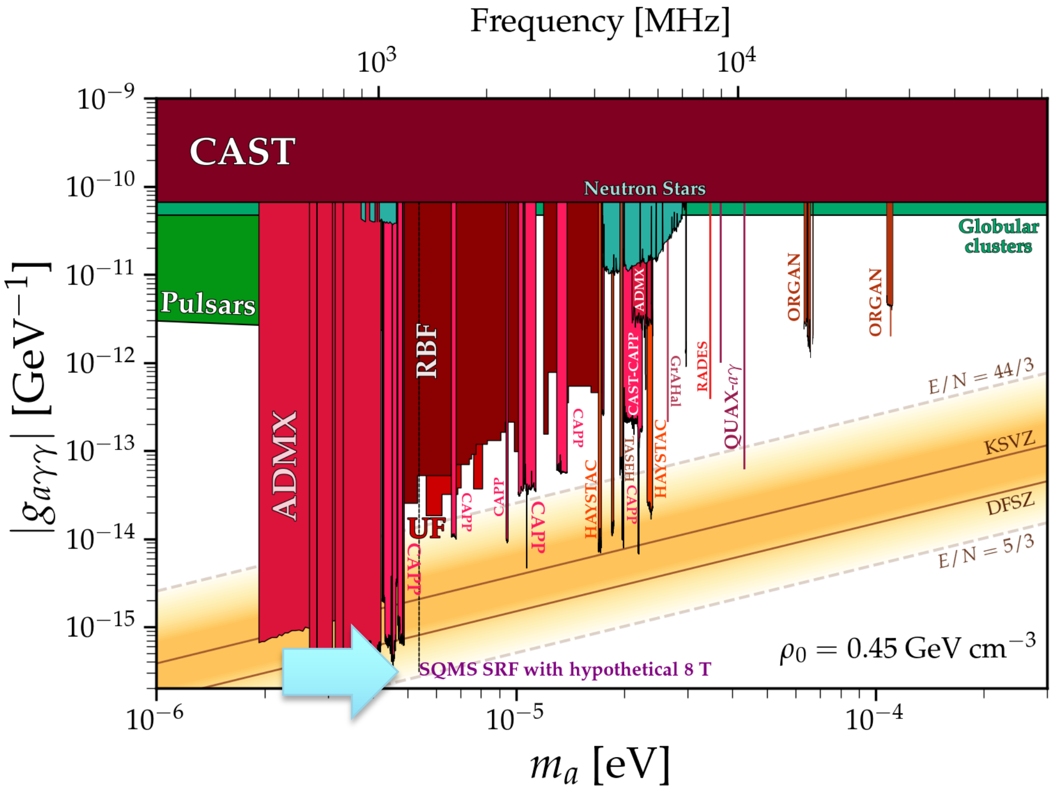
Note: photon counting estimate doesn’t yet take into account counter errors. Numerical estimates sensitive to engineering parameters.

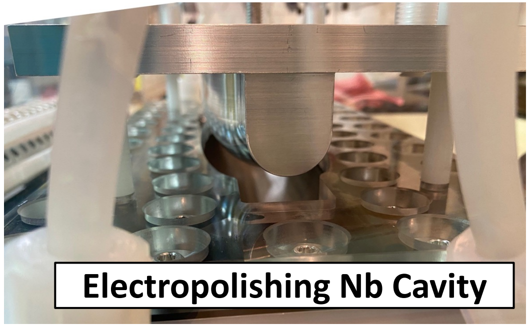
If this would work in an 8T field

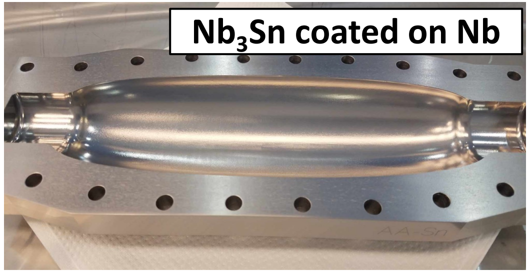


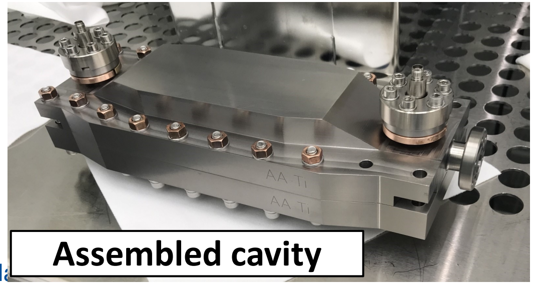
Sensitivity to **QCD axion** with single cavity and HEMT.

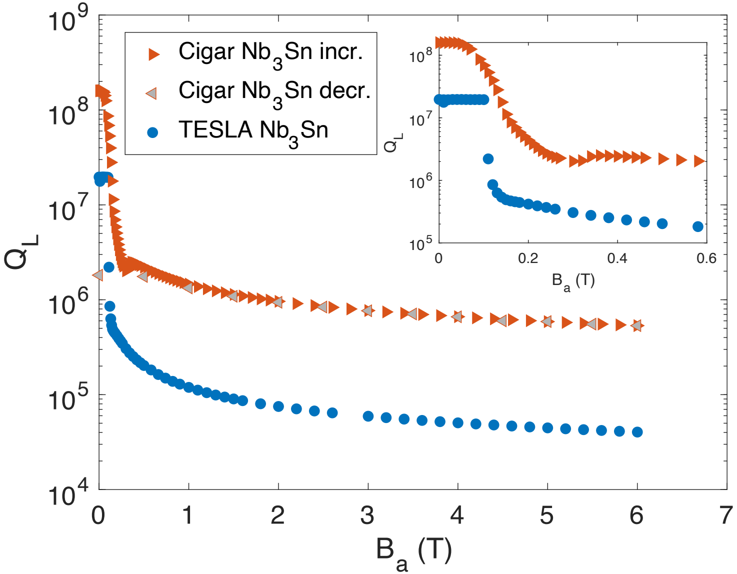
Just make $Q \sim 10^{10}$ cavities work in magnetic fields!

Nb_3Sn Cavities in Multi-Tesla Field R&D at Fermilab









Q_0 of 5×10^5 at 6 T, 4.2 K, 3.9 GHz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High-Quality-Factor Superconducting Cavities in Tesla-Scale Magnetic Fields for Dark-Matter Searches

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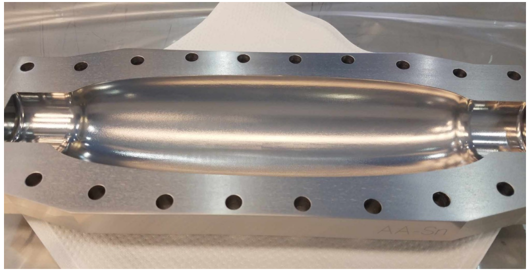
SQMS SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

FNAL Nb_3Sn Cavities for ADMX and INFN

Initial R&D at Fermilab

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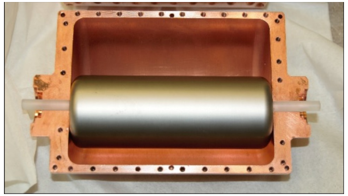
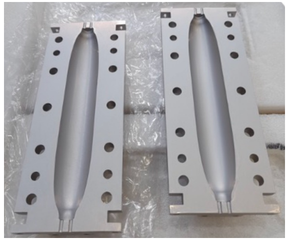
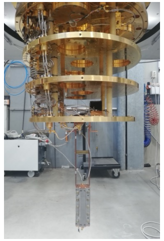
Prototypes sent to Partners



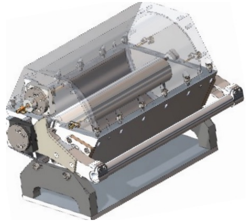
Nb_3Sn tuning rod for ADMX Sidecar sent to U. Washington (w/ LLNL)





9 GHz Nb_3Sn cavity sent to INFN Frascati for testing in 8 T fridge

Potential Future Experiments



ADMX-EFR at Fermilab

Hybrid dielectric-Nb_3Sn cavity for INFN QUAX haloscope

SQMS Center

This material is based upon work supported by the U.S. Department of Energy, Office of Science, National Quantum Information Science Research Centers, Superconducting Quantum Materials and Systems Center (SQMS) under contract number DE-AC02-07CH11359

Summarize

- Ultra-high Q cavities have achieved unprecedented sensitivity to wavelike DPDM and can boost by scan rate by orders of magnitude.
- Progress towards photon counting and high-Q cavities in magnetic fields for axion searches. Will be enabling technologies for future axion searches.